Interferometric Range Transceiver for Measuring Temporal Gravity Variations

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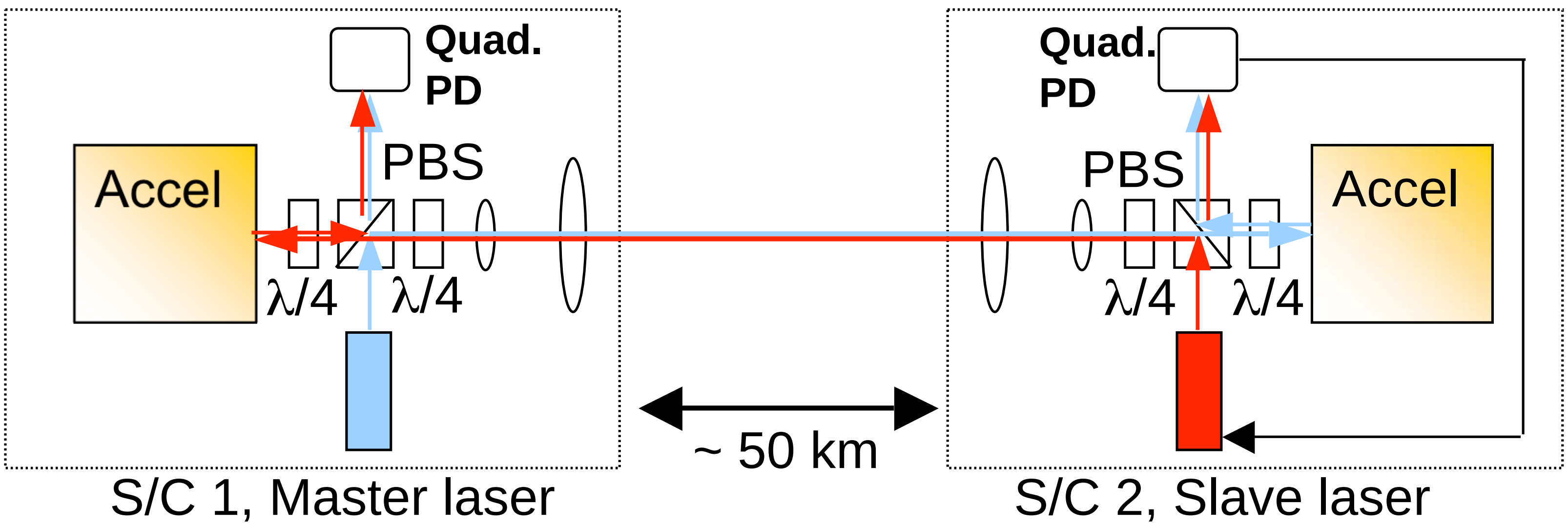
Interferometric inter-satellite ranging for improved gravity variation measurements

- Current Mission: Gravity Recovery and Climate Experiment (GRACE)
  - Provides measurements of Earth static gravity field as well as monthly estimates of time varying field
  - Launched March 2002
  - Accelerometer at CG of satellite
  - Microwave ranging between two satellites measures separation changes to ~ 1 um
  - Applications to geodesy, hydrology, glaciology, oceanography
  - www.csr.utexas.edu/grace/
- GRACE measurements are limited at low frequencies by accelerometer errors and at high frequency by microwave phase noise
- To improve spatial resolution in possible follow-on mission*
  - Improve accelerometer (LTP, LISA, ST7)
  - Implement drag-free control of spacecraft (JPL, Lisa Pathfinder, LISA)
  - $\boxed{\text{Decrease phase noise in ranging by moving to an optical interferometer}}$

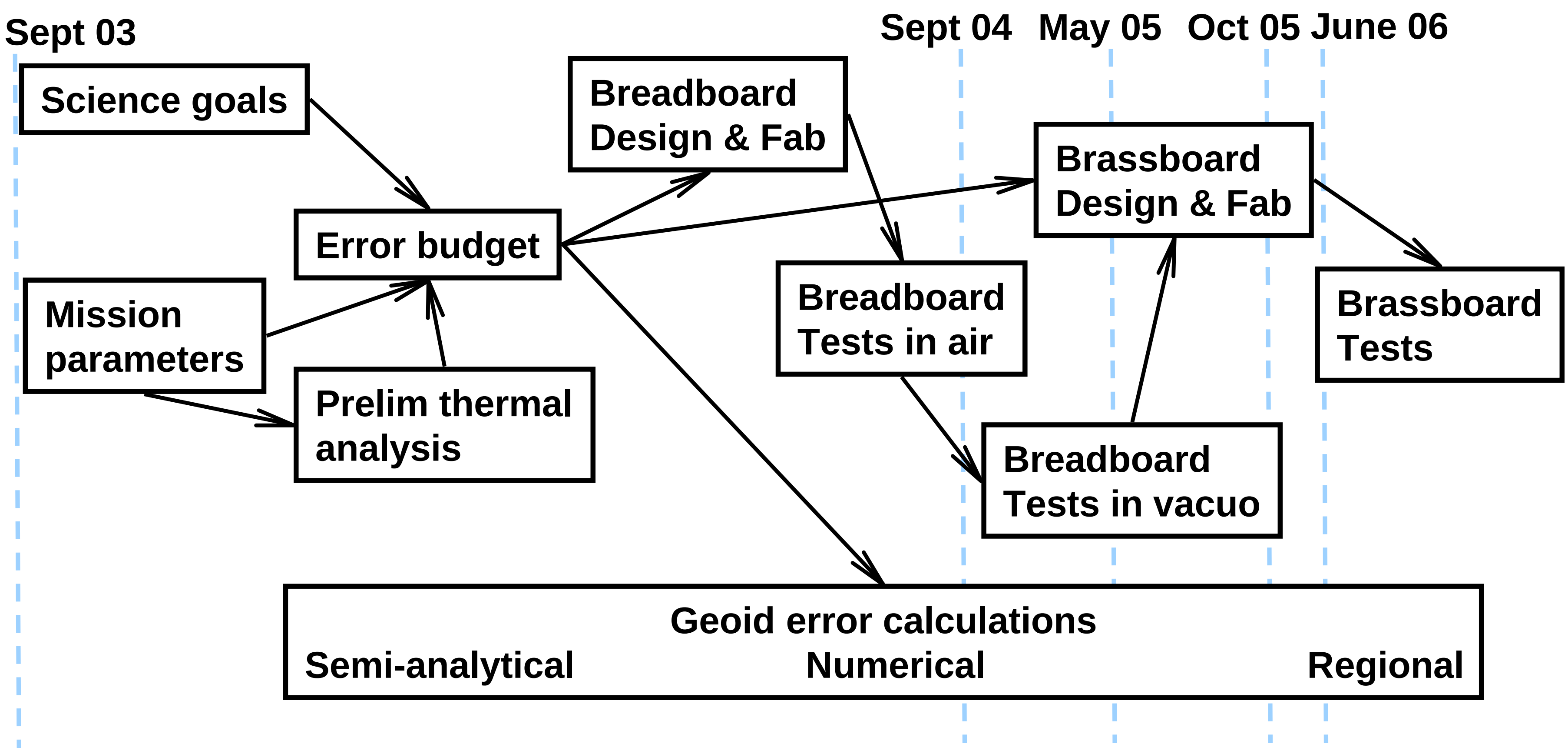
*Watkins et al. presentation at GGG2000, Banff, Canada, 2000
Bender et al. Space Sci. Rev. 108, 377-384 (2003)

Flight concept for an improved GRACE mission



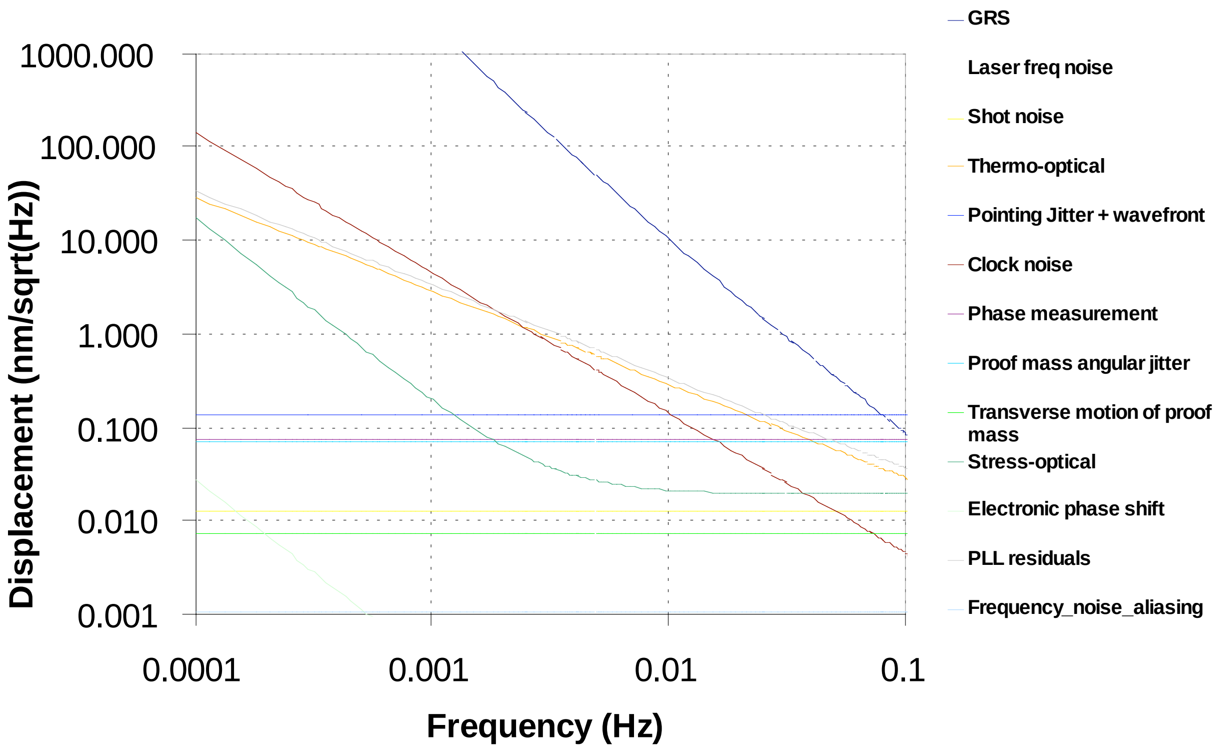
- Improved accelerometer with reflective proof mass near center of gravity of spacecraft (S/C)
- Drag-free operation of S/C
  - each S/C is controlled to follow proof mass with low-force continuous thrusters
- Ranging from proof mass to proof mass with heterodyne interferometry to 1 nm/sqrt(Hz) level over frequencies of 10 to 100 mHz
- Error analysis for improved mission

IRT Instrument Incubator Program flow



- Breadboard constructed from commercial off-the-shelf (COTS) parts
- Brassboard is a flight-like model with goal of demonstrating TRL 6
- Error analysis demonstrates predicted sensitivity based on error budget; investigating new techniques that may minimize impact of temporal aliasing on gravity field retrievals

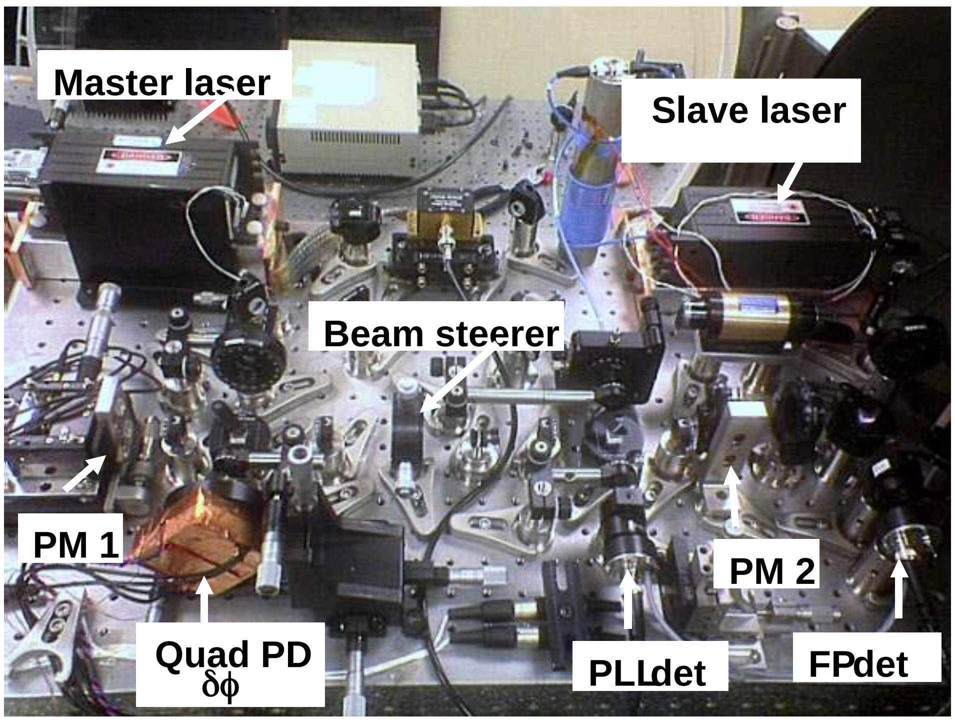
Error budget based on flight concept guides laboratory demonstration

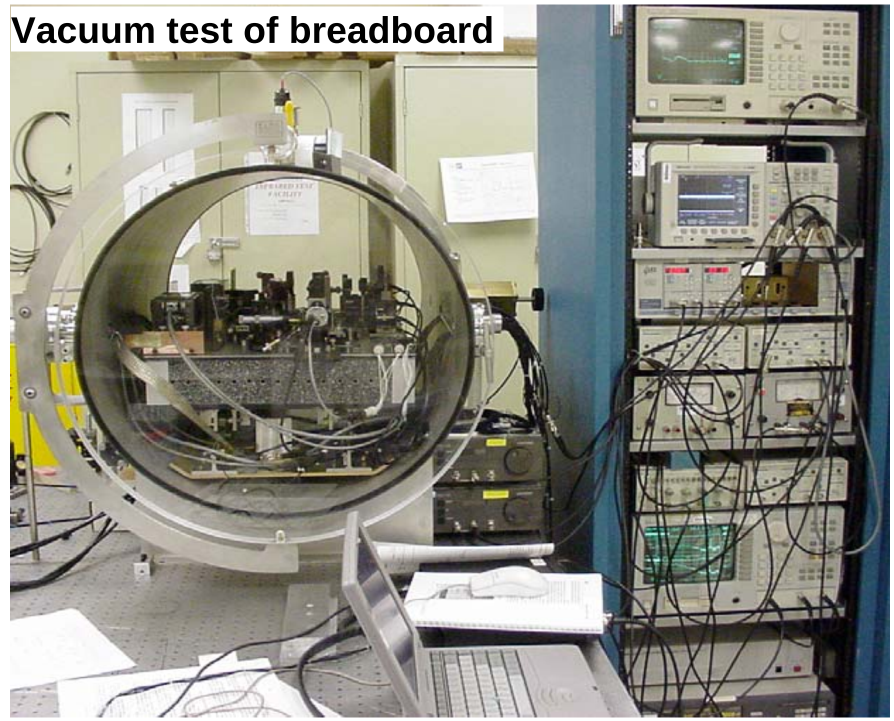


- Dominant errors will be GRS at low frequencies, laser frequency noise at high frequencies
- Low Earth Orbit (LEO) thermal environment leads to thermo-optical errors (dn/dT)
- Wavefront distortion couples with pointing jitter

IRT breadboard using COTs components used to validate several terms in error budget

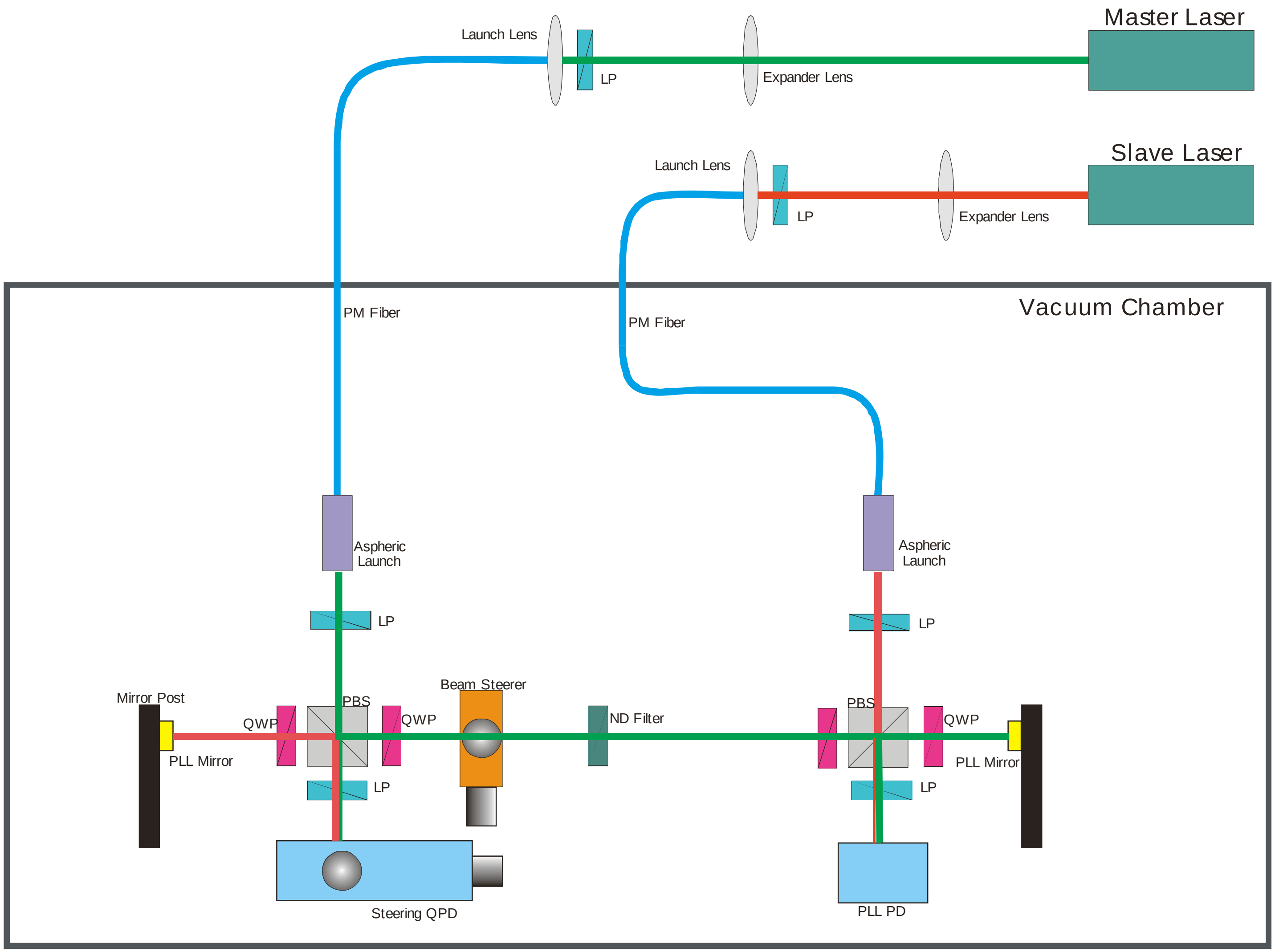
- Thermal environment uncontrolled
- Phase measurement with JPL-provided phasemeter



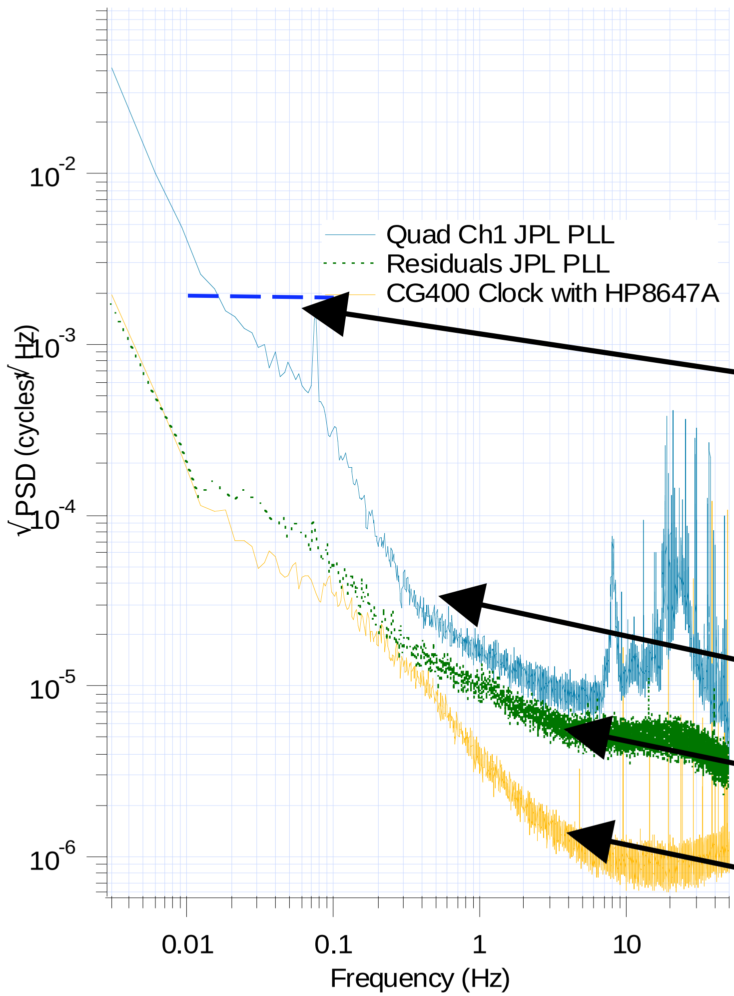


- No telescope
  - Wavefront distortion not measured
- Flat mirrors simulate proof masses

Breadboard Layout



Breadboard interferometer performance



Performance most likely limited by laser frequency noise

10 nm/√Hz

Phasemeter designed and built by JPL (Daniel Shaddock, Peter Halverson, Ian Harris, Bill Folkner) Paper B8P1

1 nm/√Hz

Required sensitivity

0.1 nm/√Hz

0.01 nm/√Hz

Ranging performance

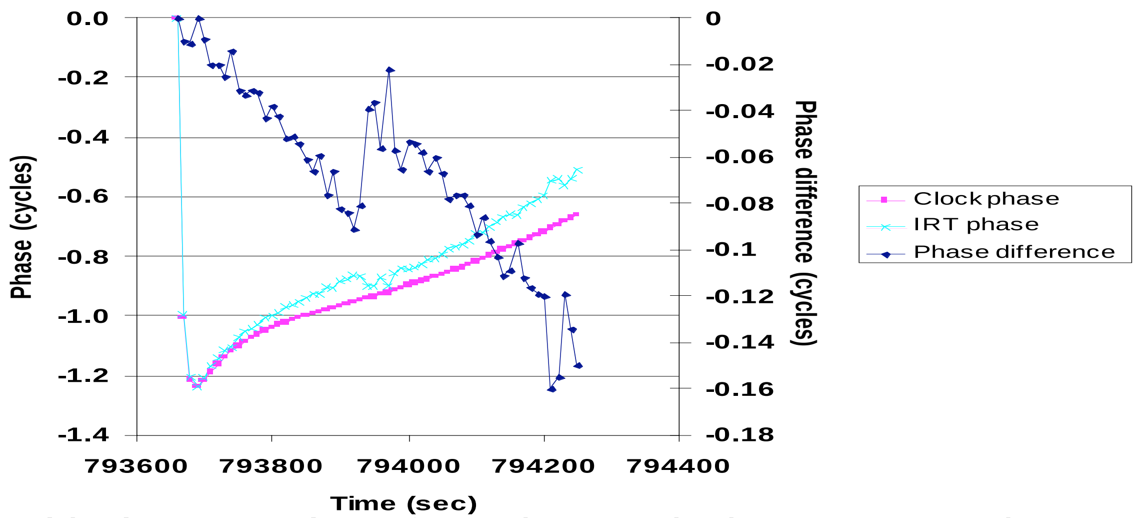
Phase-locked loop residuals

Clock noise

Error terms validated by breadboard

- *Laser frequency noise* – effect of added laser frequency noise measured at ranging output of interferometer
- *Clock noise in laser offset lock* – effect of using “dirty” clock for offset control measured at ranging output of interferometer

PLL clock phase noise is seen at output of interferometer

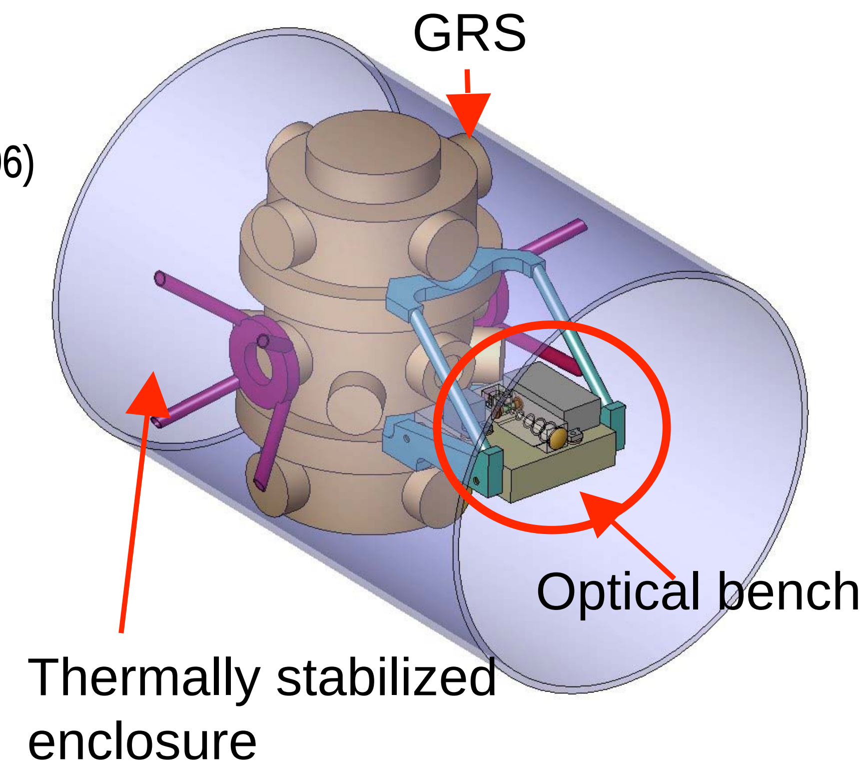


- *Phase-locked loop residuals* – error signal from phase-locked loop compared to ranging output of interferometer
- *Pointing detection scheme validated* – phase difference in heterodyne signal at quadrant photodetector measured while angular alignment of laser beam changed

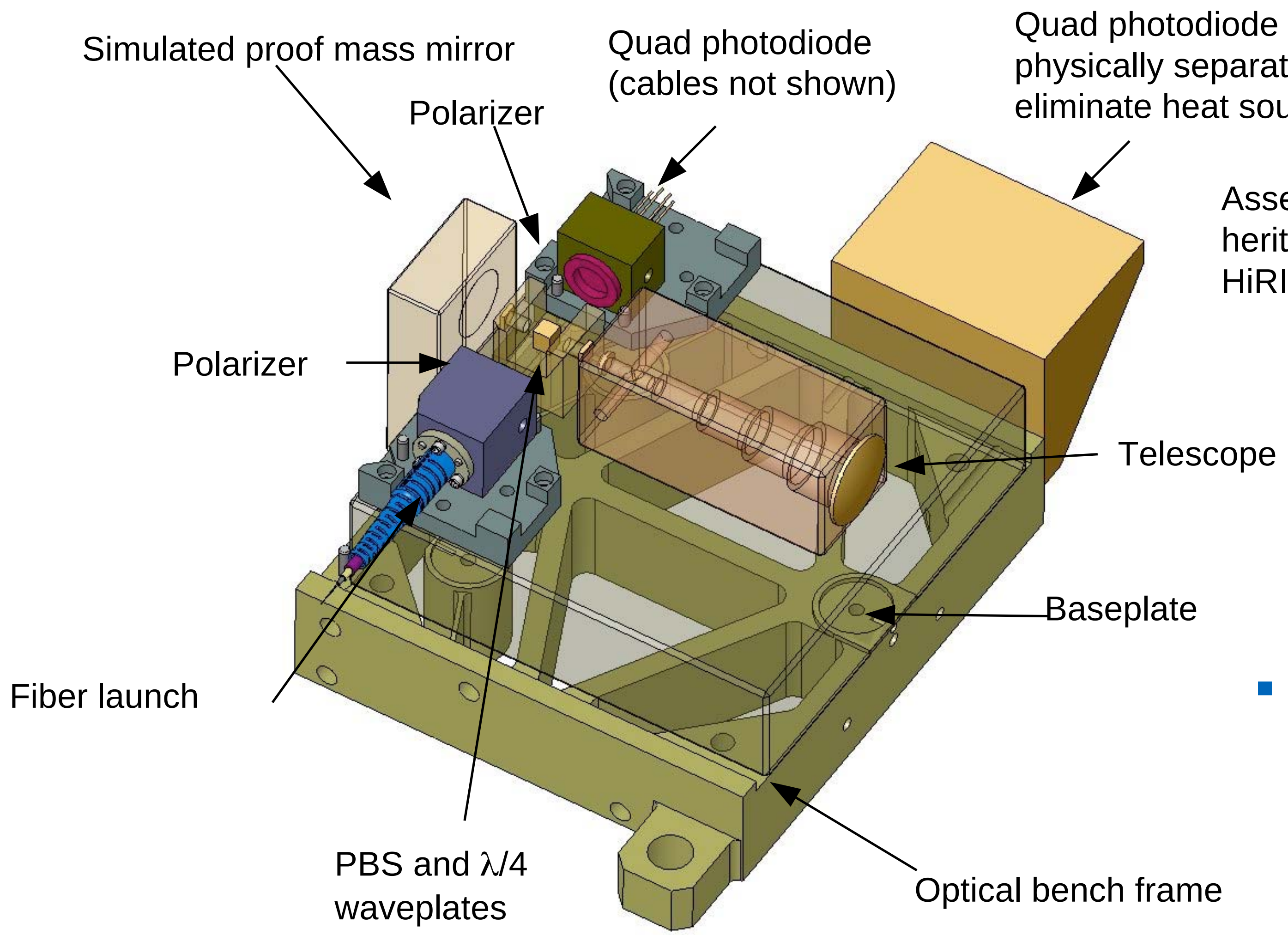
Goals for brassboard

- Demonstrate manufacturing capability for flight instrument
  - *All parts have been delivered*
  - *Test spare optical bench has been assembled*
  - *Assembly of test optical benches in progress*
- Demonstrate instrument suitability for space (TRL 06)
  - Survive launch vibrations
    - *Test spare optical bench has passed vibe tests*
  - Survive non-operational temperatures
    - *Test spare optical bench has passed non-operational temperatures*
- Demonstrate operational capabilities
  - Fundamental displacement sensitivity
  - Performance in presence of thermal fluctuations
  - Wavefront demonstration
  - Pointing measurement
  - Error budget validation
- Define interfaces to other subsystems e.g. laser, accelerometer, pointing control
  - *Interface assumptions documented*

Flight Instrument Concept



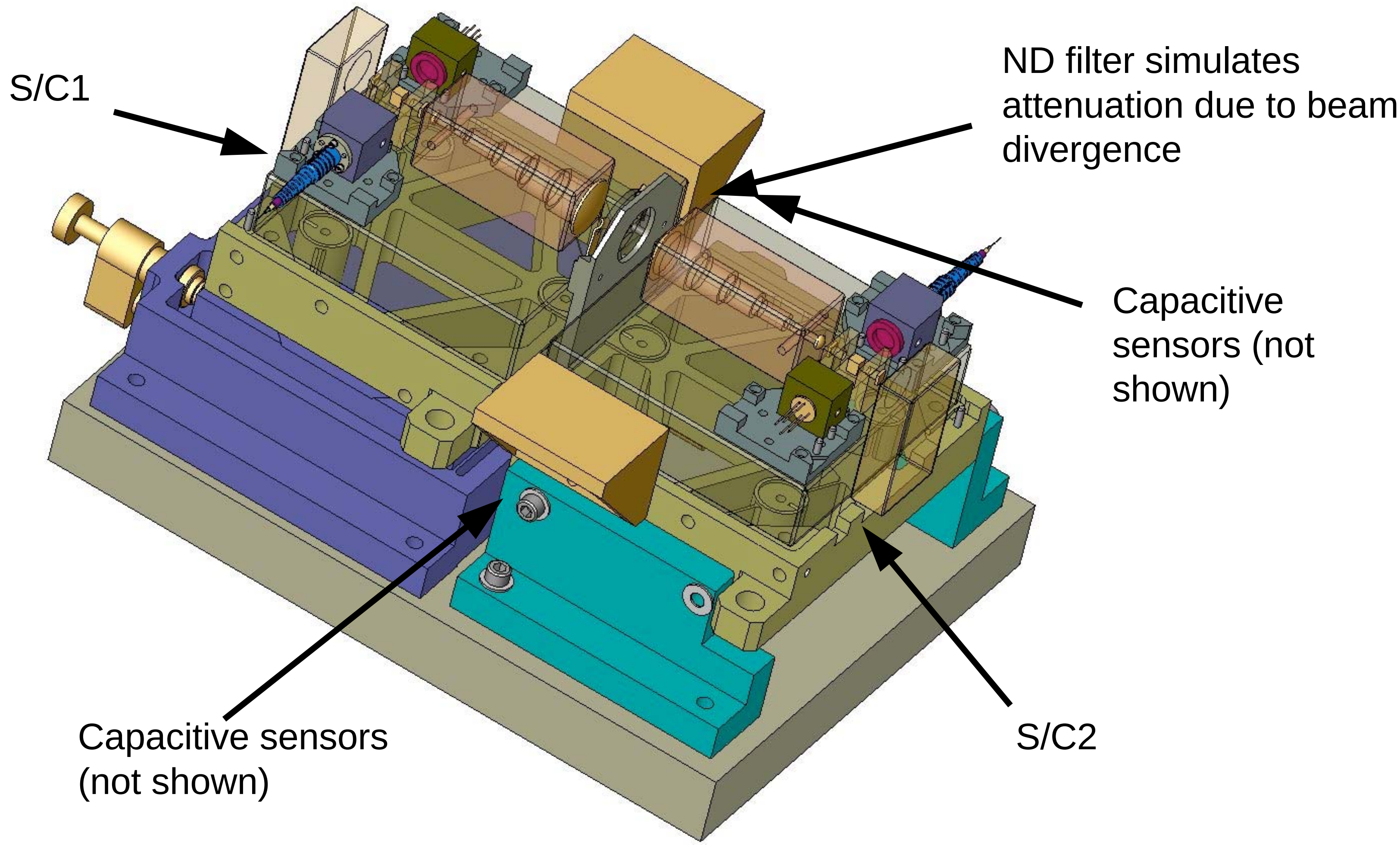
Build brassboard to demonstrate TRL 6, and for further validation of error budget



Assembly process has flight heritage from Deep Impact and HiRISE

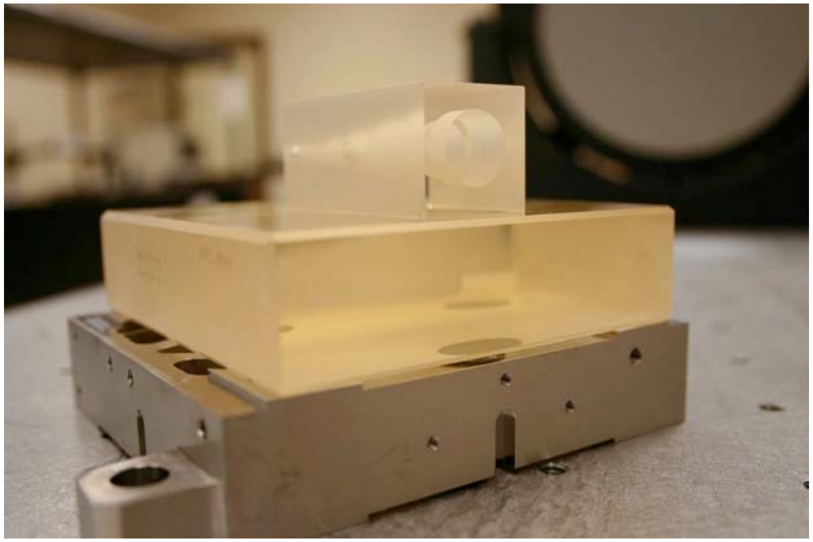
- Not included
  - *Frequency-stabilized laser*
  - *Phasemeter*
  - *Accelerometer*

Two-spacecraft test configuration



Test plan for next six months

- Performance tests of brassboard optical benches in two S/C configuration at ambient temperature
- Vibe test single optical bench
  - Pass criteria are successful re-integration and performance testing in two S/C configuration
- Non-operational thermal test single optical bench
  - Pass criteria are successful re-integration and performance testing in two S/C configuration
- Test conditions derived from NASA GEVS document



Partially assembled brassboard optical bench

Technical issues facing a future GRACE follow-on mission

- Temporal aliasing of data may limit sensitivity
- Laser reliability
- Laser frequency stabilization
- Accelerometer performance improvements
- Low-force thruster technology for drag-free control

Temporal aliasing

- Temporal aliasing: Higher frequency signals show up in monthly gravity field maps
  - Tide modeling errors
  - Atmospheric modeling errors
  - High frequency ocean signals
  - High frequency hydrologic signals
- Regional technique may help to mitigate these effects
  - Less computationally intensive - supercomputer needed to perform numerical solution to investigate spatial resolution possible with GRACE follow-on mission
  - Eliminate problems associated with spherical harmonic solutions - errors in one area propagate into the global solution
  - Possible mitigation of temporal aliasing affects - sub-monthly solutions possible
  - See Greenland results of Luthcke et al. [2006].

Laser Reliability

- Laser reliability concerns are typically fueled by the high-profile GLAS laser problems, but GRACE follow-on requirements and laser architecture differ significantly
  - Most likely cause of failure in GLAS Laser 1 is the degradation or destruction of laser diode array's gold bond wires by accelerated thermal cycle fatigue, caused by indium solder contamination.
  - GRACE Follow-on laser will operate in a much gentler thermal environment
    - Continuous output (not pulsed)
    - Lower output power than GLAS laser (~0.05 W max power vs. ~60 mJ/pulse red light)
      - Compare to 60 mJ/pulse, 40 Hz rep rate ~ 2.4 W for GLAS laser
  - Different laser architecture
    - Most likely will not have laser diode array but rather single, redundant pump diode laser
- GRACE follow-on laser derived from modest power level, CW metrology lasers with flight heritage (for example TES)

Laser Frequency Stabilization

- In order to achieve range rate errors < 1 nm/sec over 5 second intervals, laser frequency noise must be ~ $\delta\nu/\nu_0 = 10^{-14}$/sqrt(Hz) at 0.2 Hz
  - Assumes a 50 - 100 km spacecraft separation
- This level of laser frequency stability has been demonstrated in a laboratory environment
  - Notcutt et al., Optics Lett. 30, 1 (2006).
- LISA mission is developing frequency stabilized lasers for space application
  - LISA expected performance of $\delta\nu/\nu_0 = 10^{-13}$/sqrt(Hz) at 1 Hz has been demonstrated
  - This performance would result in range-rate errors of ~ 10 nm/sec over 5 second intervals
- Development of flight-qualified frequency-stabilized laser system is needed
  - Space-qualified lasers meeting power requirements are available, but the frequency-stabilization of these lasers is not.
- If sensitivity is limited by temporal aliasing, frequency stability at this level may not be required

Accelerometer Performance Improvements

- Accelerometer noise will dominate error budgets at frequencies below ~3 mHz (laser frequency noise dominates at higher frequencies)
- Our error budgets use accelerometer noise of 3×10^{-13} $*\mathrm{sqrt}(1+0.005/f)$ $\mathrm{m/sec^2/sqrt(Hz)}$
  - Approximately 300X improvement over GRACE
- Will rely on design improvements made by LISA Pathfinder/LTP mission
  - Expected performance ~3×10^{-14} $\mathrm{m/sec^2/sqrt(Hz)}$

Low Force Thrusters

- Drag-free control requires low-force thrusters for fine control of spacecraft attitude and position
- Primary risk is thruster lifetime
  - Varies with altitude
    - 0.5 – 10 mN drag for A = 0.8 m^2 and 250 – 350 km altitude
- Hall effect thrusters will provide the necessary along-track thrust; they are well developed and have flown many times
- FEEP and colloid thrusters are expected to meet the requirements for attitude control and for transverse axis drag-free control; both will be demonstrated on LISA Pathfinder mission

Conclusions

- Interferometric inter-satellite ranging provides improved measurement of gravity variations
- An error budget for inter-spacecraft interferometric ranging in LEO has been developed
- Fundamental performance limits have been demonstrated in a laboratory environment
- Work underway to demonstrate survival and performance of interferometer in relevant vibration and thermal environments
- Investigating regional error analysis techniques as a possibility to mitigate temporal aliasing
- Have identified other critical technologies and performance needed for a GRACE follow-on mission